RAPID MANUFACTURING – STATE OF THE ART, ANALYSIS AND FUTURE PERSPECTIVES.

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Abstract - Layer based manufacturing system often referred to as Rapid Prototyping (RP) have been in existence for 22 years, in the past 5 years Rapid Manufacturing (RM) has emerged from these RP systems to produce functional and structural customer focused end use components and products.
This keynote paper will review the current range of technologies for metallic systems, it will also evaluate the operating principles, features, potential and limitations of current commercially available systems.
Rapid Manufacture is increasingly being used for high value difficult to manufacture components with a new set of design rules required to fully exploit the RM systems inherent characteristics. A case studies approach will be used to show the benefits and pitfalls this new design freedom can provide designers.

INTRODUCTION

As competition within the global economy has intensified the need for manufacturers to develop and deliver new tailored products increases in order to meet the needs of the customer. Delays in development or delivery of a product could lead to loss of potential customers. To cut down on the design and production cycle a number of technologies have been put together known as Rapid Prototyping (RP) and Rapid Manufacturing (RM) (these systems are otherwise known as Additive Manufacturing or Free Form Fabrication), and "promise to revolutionise many traditional manufacturing procedures" [1]
The evolution from rapid prototyping to rapid manufacturing has fashioned a key change in the approach how products can be manufactured. Rapid manufacturing does not restrict designers from the constraints of traditional manufacturing processes, complicated geometries can be designed, changes the way manufacturers design their products and "this technology is as close to Nirvana as you're ever going to get"[2] . This has stirred the rapid development of more cost efficient (such as the Hewlett Packard 3D printer), accurate and faster manufacturing technologies which can fabricate products of high quality as well as tolerating multiple changes in both functionality and design to satisfy customer demands.
Potential trends of manufacturing industries are characterized by the complexity of products and increasing the number of variations due to various customers' preferences and increasing the competition in the global market as well.

Generally, most rapid manufacturing processes used in the fabrication of metal parts involve powder materials. "In the past two years the range of materials commercially available for direct meal laser sintering has greatly increased, and with it the range of achievable part properties and applications"[3]. Direct metal laser sintering is now an established method for the production of functional prototypes and mould inserts by means of a computer controlled laser or scanning device. This is due to the fact that these direct metal laser sintering processes and materials have developed to the extent in which some manufactured metal parts are used as a direct part. Reeves (2008) clearly states that this is very much the situation in the aerospace industry whereby production processes and materials are not totally established[4]. In addition, most metallic parts are subject to larger stresses, loading and environmental exposure than parts created from other materials. Hence, material validation of metallic rapid manufactured parts is a far greater consideration to end users than for parts produced from other materials.

Rapid Prototyping technology continued to evolve up until the late 1990's where by some authors recognized the birth of rapid manufacturing industry and so far it has continued to grow and revolutionise the manufacturing industry. Currently, there is a rising trend of rapid manufacturing technologies and as an outcome of such developments commercial OEM manufacturers are following this with the development of low cost rapid manufacturing equipments such as the Hewlett-Packard 3D desktop printer. As this technology continues to grow the cost of these equipments will continually decline in the consumer market[2]. This statement has also been embraced by so many authors in the field such as (Levy, Schindel & Kruth) "the real breakthrough of RM will mainly depend on cost and productivity improvements, which have to be accompanied with further technical progress in material properties and most of all in accuracy and reliability"[5]. The Wohler's report which is published annually is one of numerous recommended sources whereby the history and evolution of rapid prototyping to rapid manufacturing is enormously covered.

A prototype could be defined as an approximation of a physical model which serves as a standard for product

testing, in addition to design validation and implementation.
The term rapid prototyping has been defined by various authors and experts widely in the field nevertheless; these definitions for the most part concur in the fundamental ethics “rapid prototyping technology is the physical manufacture of a design, directly from digital to 3D CAD data using additive processes” (Hackney, 2007). Rapid prototyping differs from other traditional methods of fabrication such as machining with respect to milling, drilling, turning etc instead components are fabricated by the addition of materials layer by layer until the build is completed. This technology goes a long way towards reducing the cost and total build time while improving dimensional accuracy[6]

Rapid tooling is a rapid prototyping process whereby a tooling model is used in creating moulds either directly or indirectly a natural expansion of rapid prototyping[7]. points out that a major challenge that hinders rapid tooling is not being able in combining the following properties such as quality of surface, dimensional accuracy and strength together.

As advances in the development of rapid prototyping and tooling technologies increased the era of rapid manufacturing was born thus eliminating the call for most prototype and production tooling as the current development shifts towards additive manufacturing[8]. This technology (rapid manufacturing) will be offering designers some degree of freedom with respect to constraints imposed by traditional processes thereby enabling fabrication of optimised lightweight parts, design of complicated geometries [2] etc

What is Rapid Manufacturing?

Rapid manufacturing is the use or application of additive manufacturing technology in the production of finished components or products. The term RM will lead to a process whereby tooling is eliminated thus, decreasing the amount of time used in the fabrication of the component and costs [8]

The principle for the RM process begins with the generation of a CAD model which could be done (CAD model) by creating a new part in CAD, importing digitised data into a CAD package, altering an existing CAD model etc. The CAD model is converted into a standard triangulation language (STL) file which is the essential format for any rapid prototyping process. After this (STL file) is generated from the original CAD data the subsequent step is to horizontally slice the object to create a slice file (SLI) which are then combined into a final build file[9]. Depending on the surface quality required post processing may often be required such as to add extra strength to the part by filling process voids. Usually, the level of post processing depends on the final usage of the part(s) produced.

Illustration of rapid manufacturing of metal components via various rapid prototyping technologies[6] as shown in Fig. 1. It can be observed that this process is a one step process whereby prototype and production tooling is eliminated thereby reducing production cost and fabrication time. By applying any of the RP technologies a final metallic product can be fabricated.

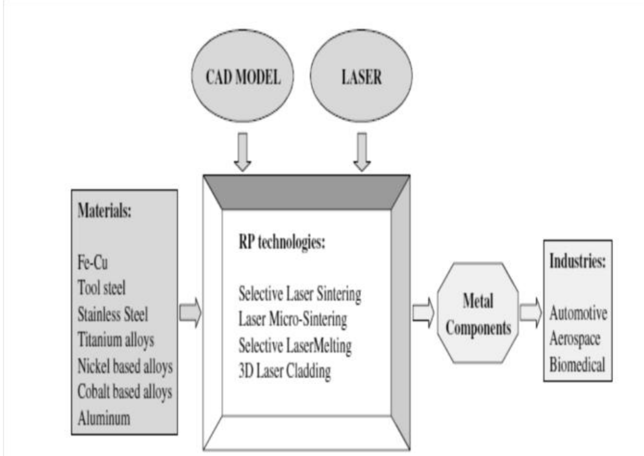

Fig. 1 Schematic representation of RM of metal components[8]

TECHNOLOGIES FOR RAPID MANUFACTURING OF METAL PARTS

At the moment more endeavour are being positioned in the manufacture of direct metal parts directly from CAD files. Currently, there are so many rapid prototyping technologies being used but RP technologies limited to RM of metal components are but a few [10].
Fig. 2 depicts a categorization of rapid manufacturing technologies used in the fabrication of metallic parts based on [11], [8]. The chief methods for rapid manufacturing of metal components is categorised into three: sheet consolidation systems, powder feed processes and powder bed processes.

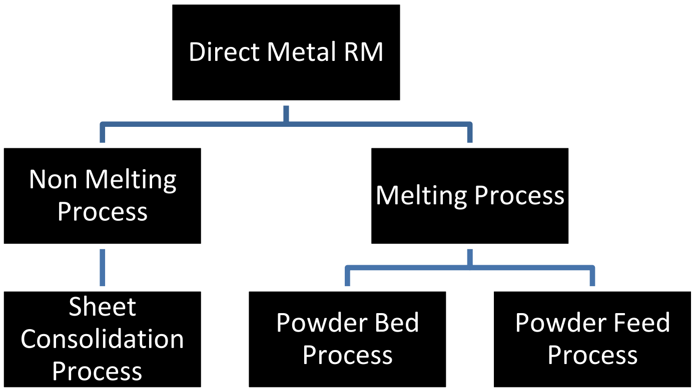

Fig. 2 Classification of rapid manufacturing technologies of metallic parts

These processes fabricates near shaped parts which may have need of some form of post processing finishing and some net shaped parts which are within the manufacturing tolerance of the CAD geometry [4]

NON MELTING RM PROCESS

Sheet Consolidation Process

The concept of sheet consolidation process has been available for quite some time. A process has been developed and adopted by Solidica Inc. a US based company in which the equipment has been dubbed Solidica Formation 2030 an Ultrasonic Consolidation technology.

The Ultrasonic Consolidation (UC) technology operates by the repetitive deposition of sheet metal in the composition of metal foil which is supported by a build platform. A rotating ultrasonic consolidation head applies sound to merge layers of metals to create and form metallurgical bonds which are then milled by CNC equipment machining (subtractive) the outline of the primary deposit into the foil. This process is continued until the process is complete Fig 3.

The ultrasonic consolidation technology combines the features of both subtractive and additive manufacturing [4,12]

Advantages of the UC process (Solidica: Technology overview, no date)

- Low process heat.
- Unattended operation.
- Very high fabrication speed.
- Material embedding.
- Dissimilar metal joining.
- Internal geometry capability.
- Stop or restarts build at any time.

Disadvantages of the UC process (Reeves, 2008)

- Processing of complex parts is restricted.
- It is a highly wasteful process (expensive ultrasonic consolidated metallic foils are machined away as waste).

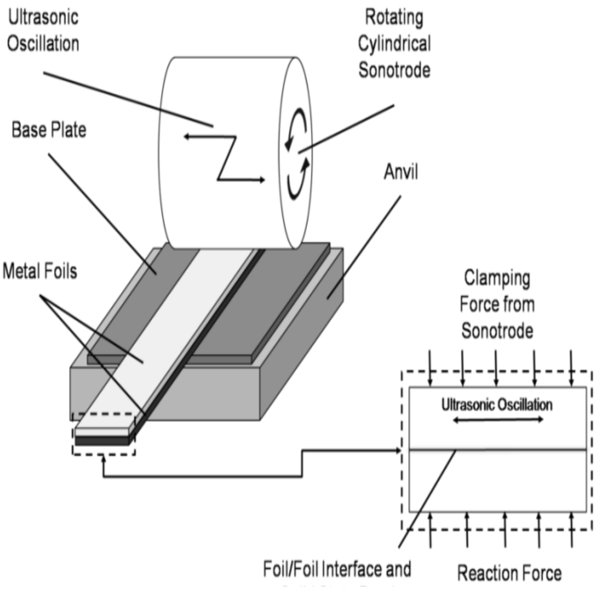

Fig 3. Ultrasonic consolidation process joining layers of metal foils [11]

MELTING RM PROCESS

Powder Bed Process

The powder bed technology [4,13] operates generally by merging a build chamber with the build platform in which the metal powder is deposited onto the latter. The build platform moves in the z-axis and is free to drop down in a series of small steps equivalent to the required layered thickness. Energy sources such as an electron and laser beam are focussed on top of the face of the build platform usually with the aid of scanning mirrors (with respect to laser beam). The beam is directed onto the surface of the build platform by means of magnetic fields in the case of an electron beam.

The powder bed process begins by spreading about 20-100 microns layer of powder on top of the build platform. After pre-heating of the build chamber, the electron or laser beam is scanned across the surface of the build platform creating a melt pool which fuses the metal powder fig 4. Through scanning the slice file (cross section and profile) a layer of the original CAD model can be fused together. The build platform is dropped down by a particular layer thickness and after which a fresh layer of metal powder is deposited on the platform fig 5.

The entire process is repeated until the entire component is finished. Chambers operating a laser beam takes place in an inert gas environment however, chambers with an electron beam operates in a vacuum chamber.

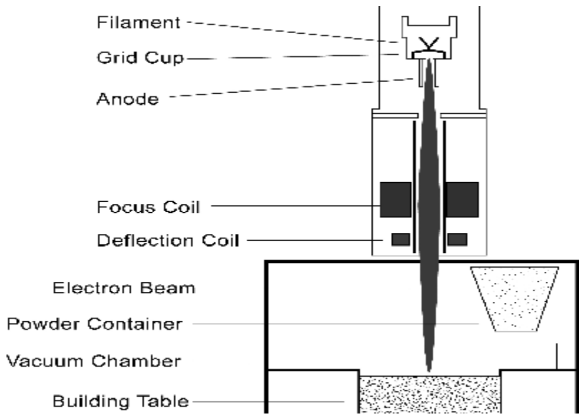

Fig. 4. Images of the electron beam process[12]

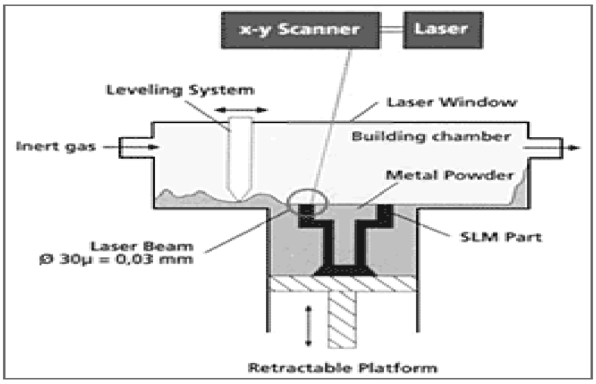

Fig. 5. The selective laser melting process

Powder Feed Process

The powder feed technologies operates primarily by taking a jet of metallic powder and directly feeding it in the direction of a high powered laser beam in other to fabricate the CAD file layer by layer. As soon as the laser beam hits the metallic powder the powder is melted. With the help of a 3 or 5 axis CNC piece of equipment the laser beam and powder feed nozzle can be controlled in that way, depositing layers of the metallic powder at high velocity onto a deposition surface at the point of meeting (between the laser beam and metallic powder). "Powder feed technologies is available either as complete machine tool systems or as modular solutions" [4]

Powder feed technologies for instance the Laser Engineered Net Shaping (LENS) as shown in Fig 6 and a number of other technologies intended as repair technology are gaining importance also are near the beginning of commercialisation.

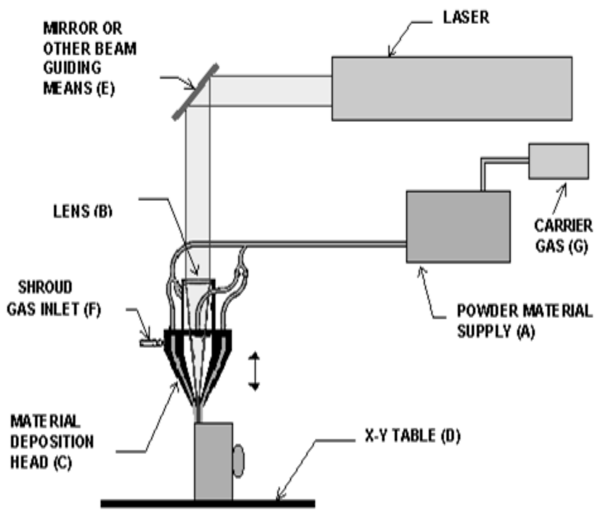

Fig.6. Powder feed process

For the powder feed systems listed, parts fabricated are near net shaped objects which will have need of some machining or post process finishing. Some metal powders which are being used for this process range mainly between stainless steel, copper, titanium, aluminium and Inconel.

Benefits of the powder feed technologies are:

- Fabricates fully dense metal parts with excellent metallurgical properties.
- They can be used to repair parts as well as fabricate them as they allow the deposition of material on top of a substrate which may well also be an existing component.
- They have good grain structures and properties similar to, or even better than the intrinsic material.
- Powder feed technologies are fast in depositing powder material as compared to the powder bed technologies.
- They have a larger build envelop compared to powder bed technologies.

Similarly, the downside of the powder bed systems provided by Reeves (2008) are that they are often too costly to operate in view of the fact that, they produce only net shaped components which necessitate machining (CNC), comprise of a huge machine foot print and have need of a large volume of an inert shielding gas to shelter the melt pool from atmospheric oxygen to promote an improved layer to layer adhesion.

Pros and Cons of Rapid Manufacturing

Manufacturing direct metal parts from 3D CAD data is a major step forward in technological development. Rapid manufacturing is being perceived as a technology that would drive the future potentials of manufacturing and these additive fabrication processes have significant importance as well as shortcomings which needs to be improved on to be able to attain a broader acceptance. As stated in Wohlers report (2010) statistics show that manufacturers of direct metal parts using additive technology has grown substantially.

Benefits and importance of rapid manufacturing include:

- The probable elimination of the time consuming and expensive method of tooling fabrication from 3D CAD data makes it economical.
- Designers are free from geometrical constraints (compared to traditional manufacturing processes) therefore, allowing them to design complex geometries.
- There is very little waste during fabrication as additive technology uses only the material needed to manufacture the component compared with traditional manufacturing processes which is subtractive removing up to 95% of the raw material to get to the final component (Hague cited in Excell and Nathan, 2010).
- It enables the fabrication of components which could be optimised (such as weight reduction) which are unattainable with traditional manufacturing techniques.
- It makes available to manufacturers the capability to fabricate components at various sites or fabricate a cost effective unit batch size at no extra cost.

Limitations of rapid manufacturing include:

- Secondary or post processing is usually required such as polishing, shot peening, support removal etc. In a manufacturing situation where by several components are being fabricated it these secondary processes could count and be time consuming.
- There is but a few choices of materials available for rapid manufacturing as compared with the widely available materials for traditional technology.

- The sizes of components are restricted by the build volume of the machine.
- Properties of the machine or process such as internal temperature, diameter of laser, layer thickness affects the precision of the machine.
- Cost of equipment and their maintenance are high which would generally relate to high cost of fabricated components.

Properties of RM Metallic Parts

Within the previous few years there have been considerable developments within the rapid manufacturing field in some significant parameters mentioned below.
The use of rapid manufactured parts are being limited to some key factors but the prevalent barrier impending relates to the shortcomings of materials[14] .
Although, additive fabricated components are now able to meet up to the standards in terms of mechanical and tensile properties when compared to machined, moulded and cast parts[15].
Academic researchers in the field such as (Ippolito, Iuliano & Gatto, 1995; Khaing, Fuh & Lu, 2001; Hackney, 2007) identifies with these key parameters which restricts the use of rapid manufacturing: dimensional accuracy, surface roughness and mechanical properties.

This aspect introduces several key properties affecting additive fabricated parts which are:

- Dimensional accuracy.
- Surface roughness.
- Mechanical properties.

Dimensional Accuracy of RM Parts

Dimensional accuracy has been identified as one of the basis of rapid manufacturing[15] yet it is still a limiting factor to today's RM processes. As an absolute manufacturing process, rapid manufacturing machinery may be considered as being able to produce net shaped and near net shaped parts. Net shaped parts are components fabricated within the dimensional tolerance to the primary CAD data whilst near net shaped parts requires some form secondary or post processing in other to achieve the required dimension.
Researches has shown that obtaining near net shaped tolerances for some RM technologies depends on certain factors such as layer thickness, temperature and build environment [16] . The research work involved tailoring steel powder particles with various surface qualities by means of the DMLS process whereby pointing out that by decreasing the layer thickness will give results to better dimensional accuracy and other parameters [16].
Other researches has shown that the dimensional accuracy levels for various rapid manufacturing technologies varies and are directly influenced by other process parameters [6], [17] . However for the direct manufacturing of tooling research has established that direct metal laser sintering (DMLS) process is the most accurate [18] [11] investigated five different SLS/SLM processes developing a benchmark Fig 7. to determine the dimensional accuracy and other parameters. Compared to other processes the DMLS process was seen to be the best in terms of geometrical analysis however, it was pointed out that *"to guarantee high accuracy the processes must take into account the laser beam spot size and thermal distortions due to successive melting and resolidification of metal material"* therefore, it is necessary to make tradeoffs between accuracy in opposition to input time and cost consideration.

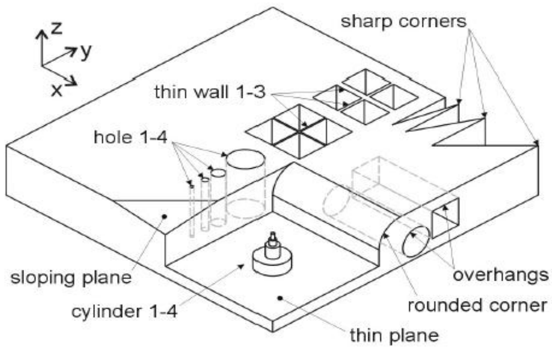

Fig. 7. Benchmark model (Kruth *et al.*, 2005)

Surface Roughness of RM Parts

Surface roughness of rapid manufactured parts are affected by three core components namely – build orientation, material composition and layer thickness[1911] given that they are built up layer by layer Fig 8.

Experiments undertaken by (Sustarsic *et al.*, 2005) determined that material morphology has a direct impact on the surface roughness another type of parameter (the type of material used and its viscosity) which has been observed to cause inconsistent layer thickness at some stage in the build phase. In addition, since the surface texture is material dependent dissimilar characteristics may be observed for the various processes.

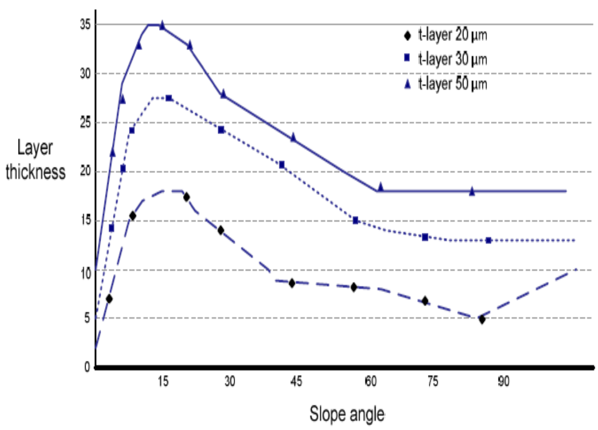

Fig. 8. Surface roughness mean for selective laser melting process as a function of the slope angle for various layer thickness

Mechanical Properties of RM Parts

In order to increase the use of rapid manufacturing technologies in the fabrication of products to begin with, the mechanical properties of the product should be guarantee through out the components life cycle.
Investigations on different SLS/SLM processes by Kruth et al. (2005)[11] identified that the yield strength of the RM processes does fulfil the requirements of manufacturing strength however, the Young's modulus stated by the manufacturer's differ with a great margin as compared to the measured values which was determined based on bending experiments.
Authors in the field has demonstrated that the mechanical properties of RM parts are considerably anisotropic and depend strongly on the build orientation [6].

APPLICATIONS OF RM - CASE STUDIES

Rapid manufacturing is broadly employed in many industries such as medical, consumer products, aerospace and automobile industries.

Automobile application

Among the early companies to take on additive manufacturing was Chrysler[6]. The motorsport industry has been one to benefit from rapid manufacturing due to their short time to deliver requirement as a part not meeting the time to launch for the race can lead to a loss of tiny proportion of seconds per lap as a result be deprived of a win (Cevolino). Illustrations of some case studies describing the application of rapid manufacturing in the fabrication of automotive components are mentioned below.

3D Systems cited in (Chua, Leong & Lim, 2009) demonstrated the advantages of creating cast metal engine block by studying the case of a 4-cylinder engine block design and manufacture for a Mercedes Benz A-class vehicle whereby exhibiting the significance in the call for short time to market[20]. The objective was intended to directly cast the engine block using a quick cast pattern fabricated by the SLA technology. The CAD data were designed by Mercedes Benz and the data transmitted to 3D Systems Technology Centre Darmstadt, wherein the block pattern was fabricated via SLA technology. The engine block pattern was used in the casting of an A356-T6 aluminium engine block of dimensions 300 x 330 x 457 mm within five weeks though the entire process took place within six weeks in contrast to conventional processes whereby it takes up to 16 – 17 weeks.

Canadian based Accufusion cited in Reeves (2008) also illustrate a case study on the development of a motorsport exhaust port resulting into a net shaped part requiring little or no secondary finishing[10] Fig 8.

Fig. 8 Motorsport exhaust fabricated via Accufusion laser consolidation process [10]

CONCLUSIONS

The development of metallic Rapid Manufacture owes its existence to Rapid Prototyping, but it is much more than a one off production system. If Rapid Manufacturing is utilised to its limits it can be an economical, cost effect and environmentally green manufacturing system. The technology is in its infantancy and yet to prove itself in many areas such build speed, accuracy, surface finish, reliability and full life cycle reliability.

The application of the technology will grow as more research and development provide improved performance and design start utilising the advantage characteristics of the process. As once Rapid Prototyping was the area of research undertaken in research centre's around the world, but is now used as the norm in the proof of design stage so will Rapid Manufacturing in the next few years.

Rapid Manufacturing provides a new design freedom with its own inherent build characteristics it will become a new stream of manufacturing focus on high value geometrically complex parts in difficult to machine materials without the considerable cost of tooling.

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